

# Resilient Urban Infrastructures – Basics of Smart Sustainable Cities

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**Abstract.** In this paper the notion of urban infrastructure resilience is formulated being expressed verbally and strictly in conditional probability terms. It is further used to formulate several most important features of a smart city. This multidisciplinary and multifaceted approach is used to explain the concept of quantitative resilience in urban design, operation, managing urban risk and mitigating of the consequences of a natural or industrial disaster. The extremely urgent problem is formulated on how to connect the physical and spatial (core) resiliencies with the functional, organizational, economic and social resiliencies.

## 1. Introduction

Currently, the concept of resilience emerged as a *central theme* of industrial and urban development (there are more than 120 definitions of resilience, most of them are qualitative). It is capable of serving as the basis and tool for solving the most urgent issues of modern civilization, including strategic investments by leading development institutions and humanitarian communities around the world. Despite the importance of critical infrastructures and systems and expected growth of future climatic hazards, relatively few studies have addressed these issues and no methodology for the analysis of such an impact has ever reached a general consensus. As of now, it seems (to our knowledge) that there is no quantitative definition of resilience and strategic preparedness to which a majority would subscribe.

The quantitative and qualitative analysis of resilience as related to urban infrastructures takes its roots from the notion and concept of industrial resilience [1-4]. In this paper the urban infrastructure resilience is defined both verbally and strictly in conditional probabilistic terms, as all the parameters which describe resilience quantitatively, are random. The conditionality of the resilience probabilities is due to the probabilistic and uncertain/fuzzy nature of the impact, and of the financial, social and other restrictions on the critical infrastructure, for which the resilience is assessed.



## 2. Short history of the resilience concept

In Russian language the word for resilience (*zhivuchest*) has as its root the Russian word *zhivoy* (alive) and means capacity of an object (animate or inanimate) to continue, without interruption, its functioning (staying “alive”), while being damaged by extreme loads, forces and/or influences. The Russian Dictionaries define *zhivuchest* as human longevity, or as capability for robust performance of a ship under the influence of wind, waves, fire, and enemy artillery. It, obviously, contains in itself the notion of endurance. The English word resilience originated from *resilire*, the Latin word meaning skip backward or rebound. In the Western world the concept of resilience as a common notion was adopted early 17-th century and, by the end of that century, the concept evolved to mean the ability to react after (not during) a shock.

It seems that Admiral O.S. Makarov of the Russian Imperial Navy was the first who introduced, way back in 1894, the notion of infrastructure resilience in reference to the ability of battle ships (as elements of the war infrastructure) to continue their effective performance under artillery fire and subsequent damage [5]. Seven years later, in 1901 the Charpy impact V-notch high strain-rate test, that determines the amount of energy absorbed by a material during fracture, was standardized, and its resilience was defined as the capacity of the test material to absorb an impact. So the modern concept of resilience comes from the metal industry, in which it is defined as the capacity of steel to withstand an impact, to maintain its shape, and to recover fast after receiving an impact. The notion of resilience was then gradually used in defining the behavior of different mechanical systems (beams, trusses, shell-like structures, bridges, as well as industrial and military vehicles and machines, etc.), and after that, used in economics, ecology and psychology [6-20].

## 3. Urban resilience

The essence and components of urban resilience consists of working to: 1) prevent any potential threat; 2) withstand any impact caused; 3) react to the crises derived from the impact; 4) recover the city's functionalities; 5) learn from the experience.

The four main components of urban resilience are: industrial disaster and climate resilience, economic resilience, social resilience and urban resilience. All this is achieved when the city becomes smart. There are two competing concepts of Smart Cities. The first concept is used to equip the infrastructures and the services for the optimal management of the city as the path to creating a Resilient City. In the second concept the optimal management of a city goes through already resilient network of services and infrastructures equipped with smart technology to create a Smart City. In the latter case the concept of a smart city is formulated and builds up around optimizing implementation of following five key ideas [6,7]:

- The win-win exchanging/sharing of goods and services between citizens and communities, using the common heritage or private property;
- The minimum environmental consumption and energy efficiency (minimal environmental footprint of the city), by recomposing the mix of energy consumption and the self-production of renewables;
- The free and fluid communication among social stakeholders (citizens, communities, companies, and institutions) using new technologies;
- City wide integration of new information and communication technologies, robotics and intelligent systems that maximize delivering needed information just in time;
- The network operation, which is the basis of resilience, to: 1) achieve maximum security of supply of goods and services with the right energy and environmental consumption; 2) make good use of the available infrastructure and 3) provide the necessary social communication that will enable the city to adapt and recover functionalities in case of an impact.

Implementation of these ideas may include changes in the design and management of: 1) infrastructures, with emphasis on the *redundancies* and *interconnections*; 2) *interdependent* services, focusing on the ways they could support each other in case of an incident; 3) *behavior of citizens* in critical situations (the fundamental strategic element for improving urban resilience).

#### 4. Quantitative description of resilience

The above *verbal* description of the resilience concept lacks tools that would allow solving numerous problems related to assessing and controlling (managing) resilience as a quantity. Below such an apparatus is described. A generalized quantitative definition of resilience and preparedness is given by taking into account that most of the multiple parameters on which resilience / preparedness is dependent, are random variables (RV), random functions or random fields (RF).

Therefore, resilience is also a RV or a RF, and also is an explicit function of time. Hence, it is possible to quantitatively define resilience (as a rough first approximation) as follows [8,9]:

$$Rsl(t) = P \left( \begin{array}{l} P(N_t < N_*(0); E < E_*; \\ \Delta RDP \leq \Delta RDP_*; \\ \Delta t_r < \Delta t_*; C \leq C_*, 0 < \tau < t \end{array} \right) \quad (1)$$

where  $P(N_t < N_*(0))$  is the probability that the number of injuries/lethalities during the incident or catastrophe (and after, while mitigating its consequences) will not exceed a specific number during the time  $t$ ;  $P(E < E_*)$  is the probability that the volume/monetary value of the environmental damage during mitigating the catastrophe will not exceed a specific value during the time  $t$ ;  $P(\Delta RDP \leq \Delta RDP_*)$  is the probability that the decrease of the regional domestic product will not be larger than a specific value during the time  $t$ ;  $P(\Delta t_r < \Delta t_*)$  is the probability that the acceptable recovery envelope time will not exceed a specific time;  $P(C \leq C_*)$  is the probability that the cost of recovery of the region will not exceed the forecasted value.

To this definition some quantitative measures should be added that refer the incident mitigation to the human factor (applied to the whole population involved in the crises): Amount of suffering – total hours of being out of the comfort zone; Number of mild, medium and serious illnesses; Numbers of injuries, limb losses and lethalities (classified by age, gender, profession).

Now the strategic preparedness would be defined as a complex characteristic of a city, which resilience parameters [see formula (1)] are not less than some benchmark values. The latter could be obtained through solving corresponding optimization problems or real life statistics.

#### 5. Critical infrastructure models

One of the most relevant problems in risk analysis of complex systems is the construction of adequate models of critical infrastructures (CIs). These models should lead to simple and effective quantitative methods of risk analysis and management of urban systems of CIs. Complex systems are characterized by that: 1) The interaction of its subsystems (elements) is hard to present explicitly; 2) The input data which describes functioning of the various elements of CIs is heterogeneous; 3) The traditional models, based on series-parallel connection of CI elements not always give an adequate description of CIs; 4) Implementation of the logic-probability models and graph theory models demands great efforts and presence of substantial prior information on the subject of research, which is not always available. Most effective in many cases are descriptions of CI as transportation, supply and Bayesian networks.

#### 6. Intrinsic specifics of critical infrastructures

Modern CIs have following indispensable components: Risk based diagnostic subsystems; Monitoring and/or control sub-system(s); Risk based integrity maintenance subsystems; Assets safety and security/defense subsystems, and other. The total risk of operating CIs is carried by its Full Group of Scenarios (100%). All these specifics should be consistently accounted for during the design, operation and risk assessment of urban PDOs and CIs.

Urban Interdependent Critical Infrastructures (ICI) networks can be considered as *conduits* and at the same time as *intermediaries* between the natural environment and the resource demands of the urban society [8-11]. ICI is also the principal source of technological hazards of the city A point

failure anywhere in the ICI can rapidly propagate through the city with broad impacts on the citizens and the environment. Hence, it stands for reason that *management of urban risk may be boiled down to management of risk for the whole urban system of ICIs*.

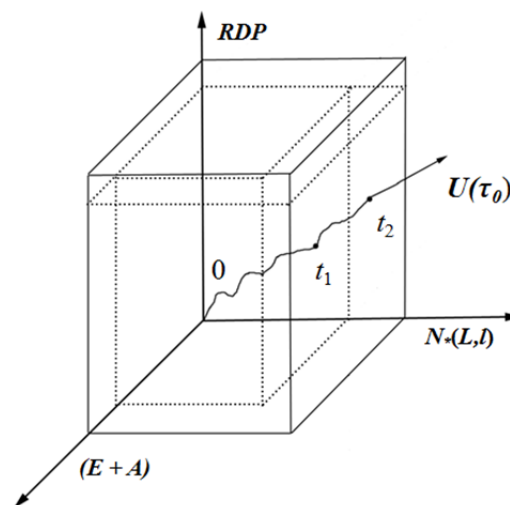
## 7. Proposed quantitative unified criteria for resilience/risk management

Author proposes [8] following four generalized criteria: ICI Resilience; Regional Average Life Expectancy (RALE); Regional Life Quality Index (RLQI); ICI Entropy. Important comment: Public safety and security is an important objective, but diminishing of risk requires additional expenditures. The share of resources that is being devoted by society for achieving safety must be continuously evaluated, having in mind other needs of society, such as clean air and water, healthy food, housing, health care, social security benefits, pensions, education, etc., which also improve the longevity and quality of life.

*Therefore, the central problem of regional (ICIs) risk management becomes optimization of the distribution of the always limited resources to improve the overall safety of systems of ICIs, and via this, the urban safety. This paper describes principles and methodology which lead to achieving this goal.*

### 7.1. Probabilistic definition of urban resilience and strategic preparedness

It is best to first visualize the Resilience Factor (see Figure 1). In it RDP = regional (urban) domestic product;  $N(L, I)$  – number of casualties ( $L$ ), injuries ( $I$ );  $(E + A)$  – environmental and property losses;  $U(\tau_0)$  – vector of full losses. The corresponding problems are solved using appropriate probabilistic methods.



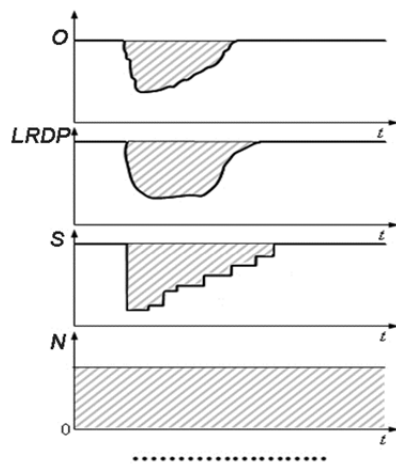
**Figure 1.** Full and partial resilience factors

Actually, Resilience Factor (RF) is a  $n$ -dimensional vector. In order to visualize each component of this vector it is recommended to deploy the vector, portraying each component of the RF vector as a two-dimensional function of time (see Figure 2). In this figure it can be seen that after the disaster the CI output  $O$  is decreased and it takes some time to restore  $O$  to pre-disaster values. The same pattern is observed for the RDP of the damaged CI. The losses  $S$  of limb and health of the citizens can be compensated, but it takes more time than in the previous case. Finally, the loss of life is permanent, as it will last forever. In reality, there will be more components of the resilient factor RF.

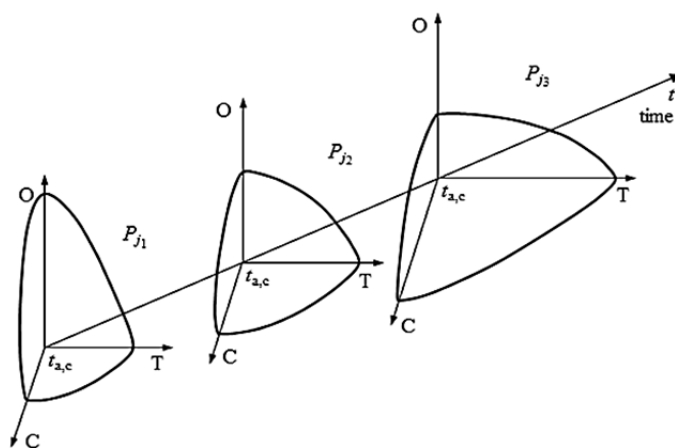
Further analysis involves considering different scenarios of development of the restoration phase of the damaged CI, each of which has its own probability of developing (Figure 3). Assessment of these probabilities is a very important, but separate part of the analysis and is derived via computer simulation.

## 8. Urban average life expectancy (UALE) as generalized criteria for optimizing city resilience

One may ask, why UALE? There are many reasons why UALE could be effectively used in urban risk analysis and management. The most valuable asset of any society is its people. The most valuable trait of a human being is her/his life. The most valuable parameter of a human life is its longevity in good health. UALE at birth is a non additive (non linear) parameter which permits combining parameters of complex safety of elements, structures and ICI systems with economic parameters of the operation and social aspects of sustainable development of the region. UALE provides seamless tying up of separate specific problems of safety/reliability of CIs and their elements with the generalized problem of regional risk management. UALE is a convenient characteristic for assessing the quality of life, because it continues to make sense with the size of the society in consideration shrinking. It is possible to calculate ALE for the nation/country as a whole, as well as for a separate region, industry, ICI, potentially dangerous object (PDO) and even for an individual. UALE has a biological «ceiling» (currently, around 125 years) and some properties of a fractal, is a solution of a system of differential equations and has the form of a logistic curve which is a function of time.



**Figure 2.**  $n$ -dimensional collapse of infrastructure operating quality due to a disaster or a catastrophe:  $O$ -Output, LRDP – Lost growth RDP,  $N$  – non recoverable losses,  $S$  – recoverable losses; the dashed area relates to the  $n$ -dimensional volume/area of the quality collapse



**Figure 3.** The change of the partial infrastructure resilience  $Res_j(t)$  in time for different probabilities of an incident/disaster/catastrophe and size of losses.  $t_{a,c}$  – time of the disaster,  $C$  – cost of recovery,  $T$  – duration of recovery,  $O$  – volume of lost production/services.

## 9. Conclusion

Initial results are presented of an interdisciplinary project on developing a methodology of urban risk management via risk governance of ICIs systems.

The proposed methodology may serve as a useful tool for managing risk of PDOs, critical infrastructures and their systems according to the RALE criterion.

Results of the research may be useful to the municipal level decision makers, who make decisions related to optimal distribution of their budgets, taking into account *sustainable* growth of entities under their jurisdiction. They will also be able to monitor how their decisions influence the quality of



life / level of happiness of their constituents as related to the decisions they make in the disaster and ordinary times.

In order to implement the resilience methodology to create a smart sustainable city it is necessary to build up for it an urban resilience subsystem *URS*, its architecture outlined in this paper, and create in its frame work a Resilience Office that is the core of dealing with urban crises and systemic stress. This *URS* would identify the weakest spots in the urban System of Systems and react faster and more efficiently during and after an impact or crisis.

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